Early Journal Content on JSTOR, Free to Anyone in the World

This article is one of nearly 500,000 scholarly works digitized and made freely available to everyone in the world by JSTOR.

Known as the Early Journal Content, this set of works include research articles, news, letters, and other writings published in more than 200 of the oldest leading academic journals. The works date from the mid-seventeenth to the early twentieth centuries.

We encourage people to read and share the Early Journal Content openly and to tell others that this resource exists. People may post this content online or redistribute in any way for non-commercial purposes.

Read more about Early Journal Content at http://about.jstor.org/participate-jstor/individuals/early-journal-content.

JSTOR is a digital library of academic journals, books, and primary source objects. JSTOR helps people discover, use, and build upon a wide range of content through a powerful research and teaching platform, and preserves this content for future generations. JSTOR is part of ITHAKA, a not-for-profit organization that also includes Ithaka S+R and Portico. For more information about JSTOR, please contact support@jstor.org.

EXPERIMENTS IN ICE MOTION.

In a previous study the author became convinced that a definite relation exists between certain deposits of glacial débris and the topography of the surface over which the ice from which they were deposited had just passed. It seemed that this relationship could only be explained by the existence of differential movements or currents in the ice bottom, and it was to determine the existence of these and, to as great an extent as possible, their nature, that the following experiments were undertaken.

Much discussion has taken place over the method of motion in glaciers and the condition of the basal portion of a thick bed of ice, such as a continental glacier. The upper parts of glaciers are known to be practically rigid, while the basal portions, as far as can be judged from the resultant topography, is possessed of differential movements, *such as might take place in a viscous body.* Whether the mobility of the bottom is caused by regelation, granulation or true viscosity, the currents would be the same and it was these alone that the author attempted to investigate.

Under the assumption that the currents were such as could take place in a viscous body, the substance chosen to experiment with was wax or paraffine in which was dissolved a quantity of refined petroleum to lower the melting point. The paraffine was melted and allowed to cool to a temperature such that it would just give under its own weight, great care being taken to keep it of an equal temperature and softness throughout The wax was than forced through long, narrow boxes, open at both ends, by means of closely fitting plungers, and caused to pass over obstructions of various kinds placed in its path. It was then allowed to cool in the box and sawn or sliced into sections. The boxes used were of varying lengths and generally about twice as high as broad, allowing for a vertical play of currents as the class of obstructions it was desired to study would produce only this kind. The face of the obstructions extended entirely across the box and was rounded but quite abrupt. The inside of the boxes was planed smooth and then rubbed with olive oil to reduce friction and consequent drag on the sides (which it was feared would influence the results of the experiment) to as great an extent as possible. In experiments upon the effect of drag it was found necessary to increase it artificially. The boxes were fastened together by screws to facilitate handling.

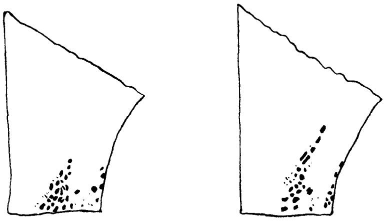


FIG. 1.

In forcing the paraffine through the boxes the strength of the operator was generally found sufficient to produce the necessary rate of motion which did not exceed a foot in fifteen or twenty minutes and was, when necessary, further reduced by pauses in the operation. In order to trace the currents thin lines of powdered coal or galena and layers of darkened wax were used. When the wax was being packed in the box the different layers were fused on the surface with a Bunsen burner and allowed to stand in contact for a few moments before being moved in order to form a perfect union and regain a temperature similar to the residue of the wax.

THE EXPERIMENTS.

Experiment 1.—A box 6 by 6 inches and 12 inches long was furnished with an escarpment 1 inch high which extended to the rear of the box. Coarsely powered galena was sprinkled upon the floor of the box and the wax packed upon it. The wax was then subjected to a shove of about 3 inches. The result is shown in Fig. 1.

Experiment 2.—A box 3 inches high by 3 inches wide was furnished with an escarpment 5/8 inch high. The wax was provided with a basal layer of darkened wax 1/2 inch thick. It was shoved 7 or 8 inches. Fig. 2.

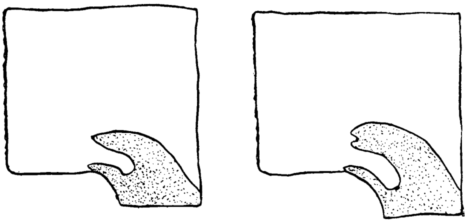


FIG. 2.

Experiment 3.—The same box as in Experiment 2 was provided with an escarpment 1 inch high and the wax provided with a thicker basal layer of darkened wax. The same length of shove was given. Fig. 3.

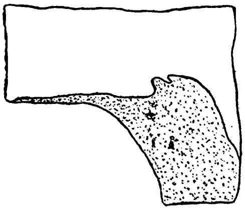
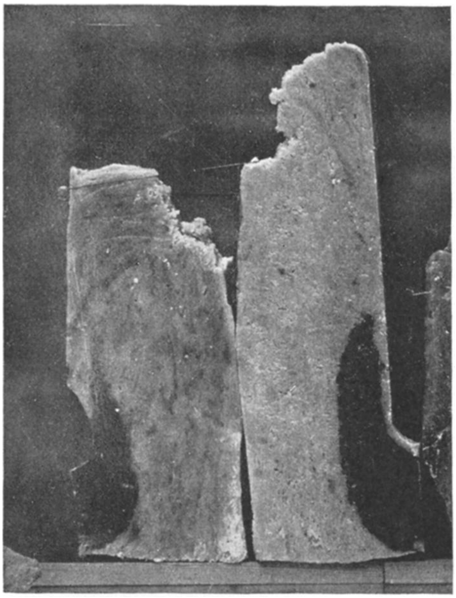


FIG. 3.

Experiment 4.—A box 3 1/2 inches wide and 6 inches high with an escarpment 7/8 inch high. The wax was provided with a basal layer of darkened wax and a little light wax, 3/4 inch, was packed between it and the escarpment. It was shoved about 13 inches. Fig. 4*a*.

Experiment 5.—The box used in Experiment 4 was provided with an obstruction 7/8 inch high and 2 1/4 long with an abrupt front and gently sloping rear. The wax was furnished with a basal layer of darkened wax and shoved about 10 inches. Fig. 4*b*.

Experiment 6.—A box 3 1/2 by 6 inches with an escarpment 1 1/2 inches high. The wax was provided with a basal layer of dark-



b FIG. 4. *a*

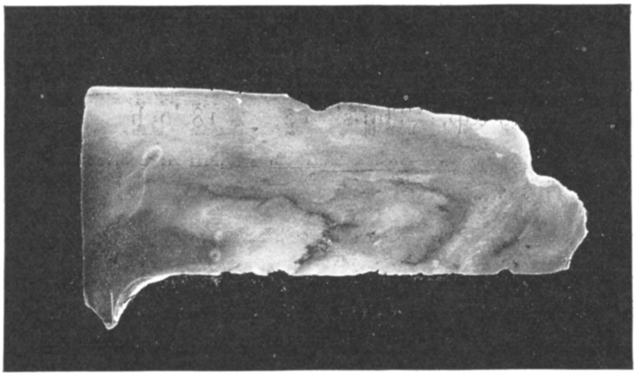


FIG. 5.

ened wax and a couple of dark lines at intervals of about ¾ inch above it. It was shoved about 12 inches, Fig. 5 (by transmitted light).

Experiment 7.—A box 4 feet long was furnished with two escarpments each ⅞ inch high. The first extended one-half the length of box and the second 14 inches from the back and lay upon the first. The wax was provided with a basal layer of dark wax and two dark lines. The shove was 18 inches. Fig. 6.

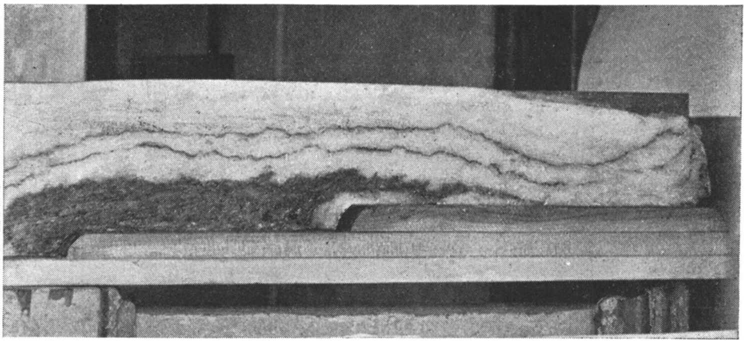


FIG. 6.

Experiment 8.—The arrangement in Experiment 7 was altered by taking 1½ inches from the upper escarpment and removing a piece 5 inches long from the lower, leaving a valley with an obstruction of 6¼ inches in front of it. The form of the base may be seen in the figure. The basal layer was substituted by a line at the level of its top. The shove was 18 inches. Fig. 7.

Experiment 9.—The last two escarpments in Experiment 8 were removed and one of the same height and 7½ inches long substituted, having a valley 10 inches long. The lines were as in Experiment 8. The shove was 18 inches. Fig. 8.

Experiment 10.—The same arrangement as in Experiment 9, but the wax was allowed to remain at rest five minutes with its front in the valley between the two escarpments. Fig. 9.

Experiment 11.—The valley was decreased to 7¾ inches by

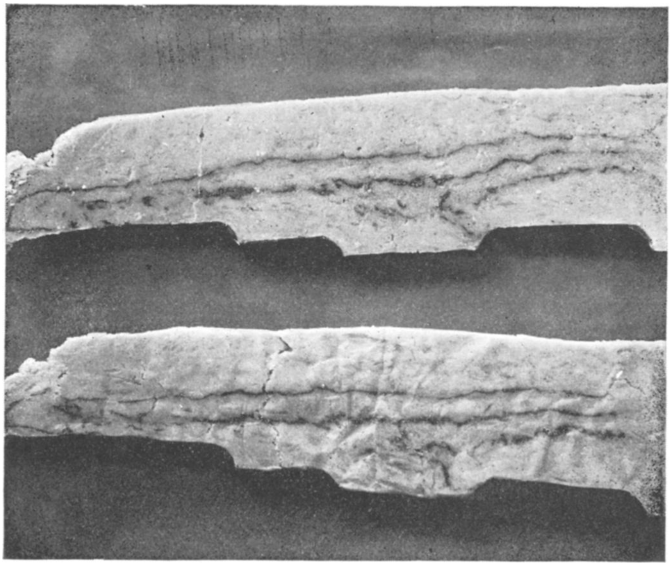


FIG. 7.

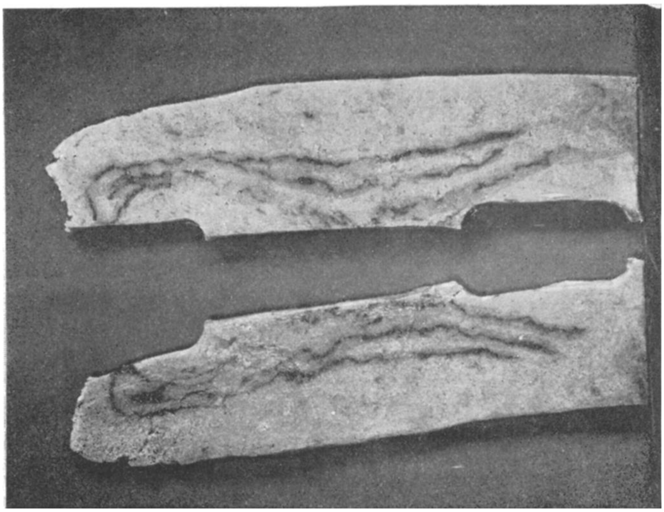


FIG. 8.

elongation of the rear escarpment and the number of lines in the wax reduced to two. Fig. 10.

RESULTS OF EXPERIMENTS.

An inspection of Figs. 1, 2, 3, 4 and 5 will show a very decided upward current produced in the basal portion of the wax. The current starts somewhat back from the escarpment and travels up and over it in an arch, leaving between itself and the top and rear portions of the escarpment a layer of white wax seemingly unaffected by the movement.

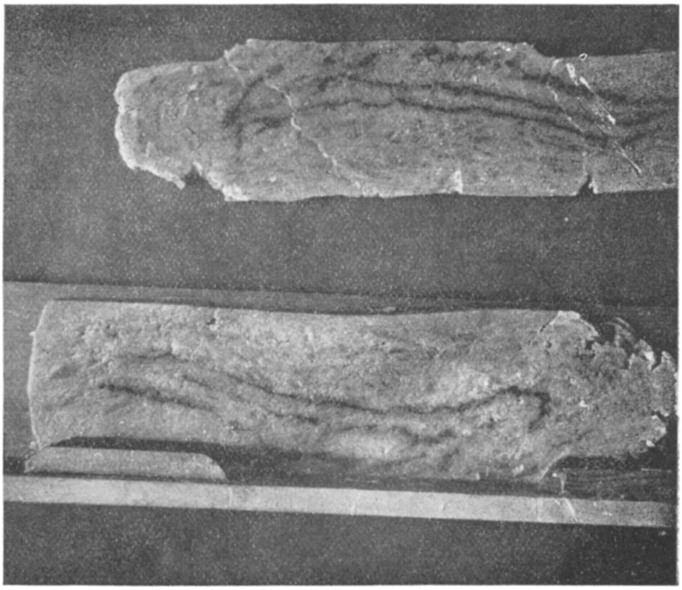


FIG. 9.

A second current is shown in the same plates creeping up close to the face of the escarpment and reaching to its top, where, upon a flat surface it may spread out closely applied to the surface, as in Fig. 3, or rise a little above it as in Fig. 2. In every case it will be noticed that this current is a very minor portion of the wax movement. In case of a further movement of the wax the evidence of two currents, so clear in Fig. 2 is obscured, as shown in Fig. 6. A close examination, however, reveals their continued presence.

In the case of an escarpment or obstruction with a subsequent declivity the basal layer is continued out into the wax from the top of the escarpment or obstruction as a narrow line. Fig 4*b*.

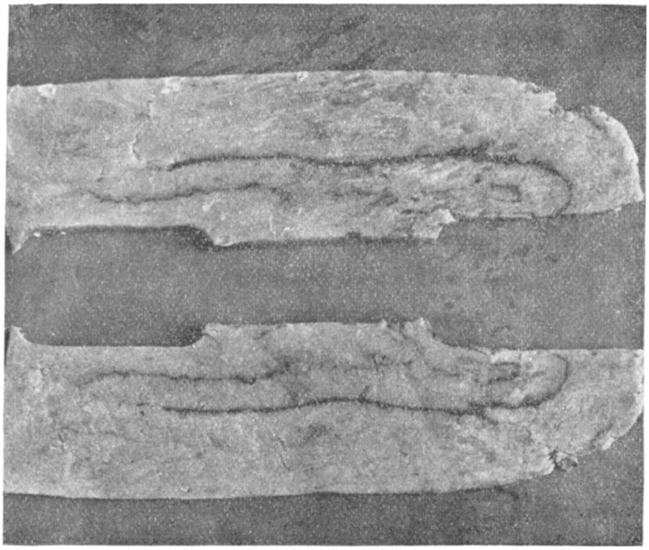


Fig. 10.

The part continued in the line is, possibly, the part noticed in Fig. 2, adhering to the face and top of the obstruction while its main current can be seen rising in an arch behind. The same feature is less prominently shown in the experiments where lines were used instead of the basal layer of darkened wax. Another point to be emphasized is the arch-like course taken by the upper and principal current. Rising abruptly a little way back from its front the currents extend to a considerable distance in its rear, where they descend in a much more gentle curve towards a point much farther from the escarpment than it originated. At all points it is free from contact with the escarpment. This is shown in Fig. 5, and in the simplest form in Fig. 4*a*, and in the upper lines at the second escarpment of Fig. 6.

In Fig. 5 the arch is shown complicated by a most important agency, namely, drag. This will be shown to be the source and explanation of some of the complicated phenomena observed in the wax. Experiment 6 was designed to determine the effects upon the moving wax of the drag from the bottom of the box. As noted above, it was necessary to induce drag. This was done by a pause in the shove allowing the wax to flatten slightly and adhere to the bottom. The currents marked by the lines in the wax descended upon the surface in the rear of the escarpment and where there retarded by friction, the upper part was carried forward by the general movement of the wax and the result is a curve reaching far to the rear of the escarpment, with a sharp curve passing back much closer to the escarpment and reaching the bottom of the box. Fig. 5 and the anterior portion of the wax in Figs. 7, 8 and 10 (in the latter it is to be noted that the curve is flattened by the unavoidable falling forward of the front of the wax as it cooled in its box).

It was now desired to ascertain what became of the recurved currents under conditions of recurring obstructions and of being carried forward over a plane surface. The first of these questions was answered incidentally in experimenting on the second, and its consideration may be retained till the last.

Experiments 7 to 11 were designed to answer the first question and the results are seen in Figs. 6, 7, 8, 9 and 10.

Experiment 7 was considered a failure because of the great reduction of the internal capacity of box and consequent acceleration of the motion of the wax and the inability of the currents to reach the bottom and become affected by drag. Fig. 6.

Experiment 8. The narrow valley and proximity of the escarpments produced a clogging of the wax and almost total disappearance of the characteristic curve, however enough remains to prove its existence. The lower layer and the second layer show drag respectively after the first and third escarpments, while the upper recurves only at the extremity.

The most important feature of the experiment is shown in the sharp angulation of the recurved portion of the upper line and of the folding upon themselves of the lower with consequent stretching out in a series of detached portions. Fig. 7.

Experiment 9 shows the same destruction of the lower line and a most remarkable elongated folding, also a recurving of the two upper ones as they arch over the last escarpment. Fig. 8. The advanced position of the rear of the upper lines is another evidence of the drag.

Experiment 10 shows identical phenomena with sharply angulated recurve just rising over an escarpment. Fig. 9.

Experiment 11 shows another form of the loops in passing an escarpment and the stretching with consequent approximation of the two ends of the loop caused by the horizontal progression of the wax. Fig. 10.

The effect produced on the loop by progression on a plane surface is clearly exemplified by the basal line in Figs. 7, 8 and 9, and in the loop at the extremity of Fig. 10. The action is to produce a stretching and close refolding of the loops, then a breaking up of the loop into sections. The result is the formation of laminæ, not of great extent themselves but in series of great extent.

It is necessary to again call attention at this point, to the phenomena shown in Experiment 5, Fig. 4*b*. The basal, dirty layer of the wax, upon reaching the summit of a rounded obstruction did not follow down the far side of the obstruction, but was carried forward in a straight line into the body of the wax leaving a portion of the rear of the obstruction untouched.

RELATION OF THE EXPERIMENTS TO OBSERVED PHENOMENA IN ICE.

While the author was engaged upon these experiments Professor Chamberlin, in his annual address as president of the Geological Society of America (Recent Glacial Studies in Greenland, Bull. Geol. Soc. of Am., Vol. VI, p. 199) reported his observations of the previous summer on the glaciers of Greenland.

His observations tallied to such a remarkable extent with the results obtained in wax by the author that it has seemed important to consider the resemblance.

In comparing the two it must be recognized that the basal layer of dirty wax represents many débris layers and laminæ at the bottom of the ice and the lines above higher series of débris layers and laminæ. The seeming disparity in size of the wax experiments with the glaciers, need not be the cause of any hesitancy in comparing the results. Professor Chamberlin places the maximum limit of dirty ice at 150 feet of the basal part and thinks that it is "chiefly confined to the lower fifty or seventy-five feet." The experiments were supposed to represent only the basal portions of the ice and a ⅞ inch escarpment in a layer 6 inches thick is strictly comparable to an obstruction 10 to 20 feet high in 50 or 100 feet of the basal part of the ice.

In regard to the passage of the ice over low prominences, he says, p. 205, "In meeting obstacles in front, the basal beds have the habit of curving upward, carrying the débris with them." Again, p. 208, "*Behavior of Ice in passing over low Prominences:* Several excellent opportunities for observing the behavior of ice in passing over low embossments were offered. From the front of the embossment there originated laminæ which extended backwards with a graceful, arching curve, much like the profile of a drumlin. A portion of the ice remained between these curving laminations and the upper and rear portions of the embossment. After reaching a point in the rear of the embossment, the laminæ curved downward with increasing rapidity until well in the lee, when they turned about with a more or less sharp curve, or even angle, and ran backward to some point not far in the rear of the embossment, where they ended. The higher laminæ made the longest curves and had the sharpest angles in the lee of the embossment. It appears obvious that the ice in the lee of the embossment moved more slowly than that above; hence the doubling of the laminæ upon themselves. It appeared upon close inspection that some of the inthrust layers described above consisted in reality of very sharply reduplicated laminæ.

It seems, therefore, that this phenomenon grades insensibly into the preceding. A study of the laminæ not associated with embossments showed many signs of doubling upon themselves in a similar way. It appears, then, that there is a gradation from laminæ that simply suffered doubling up to layers that obviously sheared upon each other and produced manifest unconformity and overthrust." Compare the figures of this paper and Chamberlin's, Fig. 4, Pl. IV. Figs. 11 and 12, Pl. VIII.

The above might well serve as a description of the results of the experiments on the passage of wax over escarpments and the effect of drag. It might also serve as well to describe the formation of laminæ in wax, especially when supplemented by the following (p. 204): "The débris layers are not all uniform in their distribution. Often they have much regularity and persistence; often they thin out and disappear within a short distance; more often still they persist for a few rods and are replaced by adjoining layers which come in as these thin out. Thus a belt of layers has much persistence, while the constituent layers are freely entering and vanishing. Lenses of débris occasionally appear among the layers, and a doubling back of the layers upon themselves, giving a lenticular section is not uncommon." Compare this description with Figs. 7–10.

The action of the loops caused by drag in passing obstructions is not discussed by Professor Chamberlin, but Figs. 6, Pl. V, of his article is almost identical in its main features with the anterior part of Figs. 9–10 of the present experiments.

In discussing the origin of the stratification Professor Chamberlin brings forward the hypothesis of the shearing motion between superincumbent layers of ice, citing as proof, the observation of fluting in the interpolated laminæ of débris and the breaking of fallen blocks of ice along definite planes. "But," he says, p. 207, "the best evidence of the verity of shearing between ice-plates lies in the intrusion of the earthy material itself. I was fortunate enough unless I misinterpret, to observe the actual process of intrusion. The best illustration was found on the north side of a short lobe of the great ice-cap designated the

Gable glacier. Just back of the point of observation there was a large embossment of rock, which expressed itself at the surface of the ice by a beautiful half dome, like the Half Dome of the Yosemite. The other half of the dome was cut away, revealing the operations at the base within Here it was observed that the trains of débris, apparently rubbed from the surface of the embossment, were being carried out almost horizontally into the ice in its lee. Some of these were short, while others extended several rods into the ice. They were somewhat inclined downward, but the slope of the glacier being greater, they passed out into the body instead of following the base of the ice. At one point the overthrust reached such a degree as to carry the earthy layers obliquely almost across the thickness of the glacier, producing a pronounced unconformity. (Figs 9 and 10, Pl. VII., Chamberlin.) . . . The mode of operation seems to be this: When the ice is forced over a prominence it settles down a little in its lee, and is then protected somewhat from the thrust of the ice behind; the next ice that passes over, being prevented by the former portion from settling down at once, is thrust forward over it. To some extent this is accomplished by the bending and doubling of the layers, and to some extent by distinct shearing. At length, however, the first layer is compelled by the general friction to move somewhat forward, and in time to join the common moving mass, carrying the overthrust layer of débris between it and the ice layer above. The way is then open for a repetition of the process. This picture of the behavior of the ice is quite radically different from that entertained by the viscous hypothesis, in which the ice is supposed to flow down the lee side of a prominence, as if it were a liquid. The motive power here seems not so much gravitation pulling a fluent body forward as the thrust of a rigid body by a force in the rear."

The descriptive part of this would answer, especially in the first case cited, as a perfect description of the results of Experiment 5, Fig. 4*b*. But the explanation cannot be accepted as applying to the results produced in the experiments because they were obtained in warm wax, a viscous body, incapable of shear along definite planes, at least under the very slow movement to which it was subjected. The phenomena may be explained fully as well by recourse to the drag of the bottom. The lower layers of the ice were retarded while the upper flowed over the obstruction and onto its rear face. It was there protected from further push as well as retarded, and the lower layers having meanwhile backed up against the front of the escarpment, overflowed and passed out into the ice in a horizontal line resulting from a stretching of the viscous body as seen in all the experiments. It is to be noted that while the general depression of a viscous mass is caused by the pull of gravitation, the motion at any one point is due to the motion of the mass behind it and is largely a shove, rather than a pull.

The result arrived at by Professor Chamberlin from his observations was that the ice was rigid in great part and moved along planes of shear between well individualized layers. He says, p. 212: "My observations seems adverse to anything which can be properly termed viscous fluency." And again, p. 213: "Everywhere the aspect of the ice was that of rigidity rather than viscous fluency. The rigidity, to be sure, did not prevent contortions and foldings of the laminations, such as take place in the crystalline rocks, but faulting and vein structures also occur, and there seems no more occasion to assume viscosity in the one case than in the other. Even if a certain measure of viscosity be admitted, it does not follow that viscosity was an essential agent in motion."

From the peculiarly perfect manner in which the results of the experiments in wax and the observed phenomena in the ice parallel each other, it seems that the obvervations of Professor Chamberlin may be interpreted in a slightly different manner and that his "certain measure of viscosity" may have afforded a very considerable part in the mechanics of the ice bottom. At least some method of movement must be admitted which will produce currents such as would be produced in a viscous body under like conditions. And this motion, it seems to me, cannot be produced by shearing alone.

RELATION OF THE CURRENTS TO THE SUBGLACIAL TOPOGRAPHY.

It seems from the above to be fairly well proven that differential currents, vertical and horizontal, do exist in the bottom portion of the ice, and recognizing their existence it is possible to attempt the explanation of certain features of subglacial topography. It can be shown that great drumlin-covered drift deposits lie in the lee of escarpments, or other irregularities of the surface, composed of hard rocks, over which the ice has just passed.

The upward currents produced at the front of an escarpment and extending over it in an arch have already been pointed out. The active portion of the ice bottom is undoubtedly in the region of the descending currents and the portion below the arch must be one of very slight activity. In speaking of drumlins Professor Chamberlin mentions this curve and says, p. 216: "I suspect that this is the true drumlinoid curve and that it represents the balance or the accommodation between the force of the overthrust of the over-riding ice on the one side and the friction and resistance of the ice and débris against the embossment on the other. I suspect that the progressive tendency in such a case is toward the accumulation of débris below the drumlinoid line, which was apparently a line of shearing, and that the result of such an accumulation would be a drumlin."

This idea was also entertained by the author and applied to the formation not only of drumlins but to the larger deposits of drift. It will be easily seen that in passing large escarpments the base of the proportionally large arch currents would be thrown into minor arching currents by minor irregularities on the escarpment. The large arches would have under them regions of relatively smaller ice motion with consequent deposition of débris; the point of descent of the current would determine regions of erosion. This action will be clearly seen by reference to the diagram, Fig. 11. A line was taken from Sodus Bay on Lake Ontario to a few miles south of Ithaca, N. Y., taking in the deepest part of Cayuga Lake. Upon this line is projected the extremes of elevation in surface a few miles to each side of it.

It will be seen how currents might rise from the bottom of Lake Ontario passing in an arch over the drift-covered region south of the lake and then descend to aid in the excavation of the bed of Cayuga Lake.

The minor irregularities of the Medina conglomerate, bordering this portion of the shore of Lake Ontario, produced minor and differential currents in bottom of the great arch and formed the drumlins. This diagram would apply with slight modifications of detail to a large majority of the known drumlin regions.

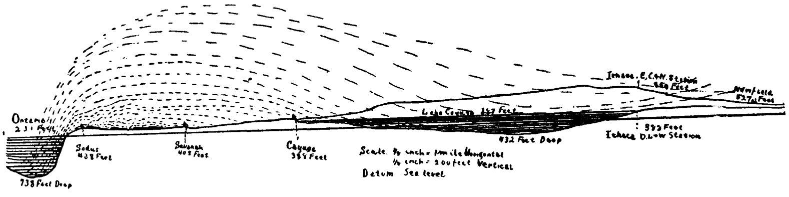


FIG. 11.

The formation of the elongated drumlins may find an explanation in the stretching out of the débris into the ice from the top of an obstruction. If toward the end of the glaciation the drift should become of sufficient thickness, it might in spots clog up under the ice and become sufficiently resistant to cause upward currents in the ice. Its face would be moulded to its steeper form by the minor currents which creep up the face of an escarpment or obstruction (Expt. 2, Fig. 2), and are perhaps responsible for the characteristic steeper slope of the face of all subglacial erosion forms. The currents of inthrust débris would arise from the heaps of débris and extend forward into the ice a short distance, while still under the arch of the currents they would gradually sink and build up the rear of the drumlin into the elongated form. The elongation and building up of the drumlin would tend to keep the currents from descending and would lengthen the arch till drumlins two miles long might be formed as noted in New York.

One other action must be noticed, namely, the moulding power of the ice currents upon a thick sheet of till. It has been claimed by various authors that the formation of drumlins was due to the erosion of a thick sheet of till by differential currents in the ice bottom. If this hypothesis is a true one, the source of the currents is readily found in the passage of ice over escarpments and other irregularities. It seems that the presence of the arched currents with regions of relatively inactive ice below over drumlin regions must give the weight of evidence largely to the theory of deposition, though the points of descent of the currents were points of erosion, in all probability, and these must have had some influence in determining the exact location and form of the drumlins.

E. C. CASE.

GEOLOGICAL LABORATORY, CORNELL UNIVERSITY,
May, 1895.